AD-A158 726 STUDIES OF GRAVITY WAVE PROPAGATION IN THE MIDDLE ATMOSPHERE(U) PHYSICAL DYNAMICS INC BELLEVUE WA T J DUNKERTON 25 MAR 85 PD-NW-85-330R AFOSR-TR-85-0505 1/1

UNCLASSIFIED F49620-83-C-0061 F/G 4/1 NL

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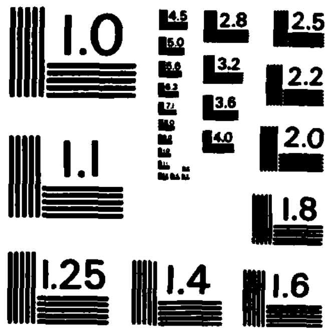

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AD-A158 726

PD-NW-85-330R

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Timothy J. Dunkerton
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300 120th Ave. NE, Bldg. 7
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25 March 1985

Annual Report
Contract #F49620-83-C-0061

Prepared for
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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85 8 20 195

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Uncl

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE
n/a

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
PD-NW-85-330R

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 85-0505

6a. NAME OF PERFORMING ORGANIZATION
Physical Dynamics, Inc.

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Air Force Office of Scientific Research

6c. ADDRESS *(City, State and ZIP Code)*
P.O. Box 3027
Bellevue, WA 98009

7b. ADDRESS *(City, State and ZIP Code)*
Bolling AFB
Washington, DC 20332

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
Same as # 7

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F49620-83-C-0061

8c. ADDRESS *(City, State and ZIP Code)*

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2310	A1	

11. TITLE *(Include Security Classification)*
STUDIES OF GRAVITY WAVE PROPAGATION IN THE MIDDLE ATMOSPHERE

12. PERSONAL AUTHOR(S)
Timothy J. Dunkerton

13a. TYPE OF REPORT
Annual Report

13b. TIME COVERED
FROM 11 Feb 84 TO 11 Feb 85

14. DATE OF REPORT *(Yr., Mo., Day)*
25 March 1985

15. PAGE COUNT
24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
gravity waves, critical layers

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Research supported by Contract F49620-83-C-0061 represents an effort to understand the role of gravity waves in the general circulation of the atmosphere. Such waves exist on a wide range of scales and frequencies. In this report, we describe ray tracing of gravity waves of horizontal scales from 50 to 800 km, all of which are observed in the middle atmosphere and play an essential role in the transport of momentum and mixing of constituents. Also presented are numerical simulations of gravity wave, mean-flow interaction, focusing on two aspects of this process: saturation and self-acceleration. Model results are compared to the predictions of a semi-analytic model of gravity waves. Finally, the report concludes with a discussion of constituent mixing in gravity wave breakdown, and problems in this area meriting further study.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☑ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
Lt. Col Dittlecner

22b. TELEPHONE NUMBER *(Include Area Code)*
(202) 767-4960

22c. OFFICE SYMBOL
NC

DD FORM 1473, 83 APR

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Uncl

SECURITY CLASSIFICATION OF THIS PAGE

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I. STATEMENT OF PROBLEM

Gravity waves are essential in the middle atmosphere, primarily in two ways: momentum transport and constituent mixing. These oscillations are characterized by rather short vertical scales (1-10 km typically) and relatively high frequencies (a few minutes to several hours). Many different observational techniques have been used to study gravity waves, including meteor trails, airglow emissions, rocketsondes, various radars, lidars, balloons, and (for the longest scales only) satellite radiometers. Unfortunately, the present understanding of these waves is not commensurate with the existing data base, mainly for two reasons. First, the theory of gravity waves is still in its infancy, particularly insofar as nonlinear gravity wave interactions and instabilities are concerned. Second, the observational community has operated in relative isolation from theoreticians (at least until recently), the unfortunate consequence of which is that measured parameters are not always sufficient for theoretical interpretation. A classic example is the measurement of frequency relative to the ground, while theoreticians eagerly await a determination of intrinsic or Doppler-shifted frequency that appears in their theory. Clearly there is room for observational improvement as well as an expansion of the current data base to cover the entire globe. Existing observations have established without doubt that gravity waves are essential to the atmospheric circulation, especially the mesosphere and lower thermosphere.

In this report, emphasis is given to the theoretical understanding of gravity wave propagation and breakdown, with a view towards enhancing present observational coverage in those areas where gravity waves might be most important. Specific aspects of the following discussion include ray tracing of gravity waves (Section II), numerical studies of gravity waves, mean-flow interaction (Section III), and some pertinent thoughts on constituent mixing in gravity wave breakdown (Section IV). The report concludes with a discussion of current theoretical and observational problems.

II. RAY TRACING STUDIES OF GRAVITY WAVES

According to linear WKB wave theory, vertically-propagating gravity waves exist for any intrinsic frequency $\hat{\omega}$ lying in the interval

$$f^2 < \hat{\omega}^2 < N^2 \tag{2.1}$$

where N is Brunt-Vasala frequency and f is the Coriolis parameter. In mid-latitudes, gravity wave <u>intrinsic</u> periods are typically restricted to the range 5 min to 15 hours (approximately). Emphasis is given to the term "intrinsic" since, for example, stationary waves may also propagate vertically in a nonzero mean flow $\bar{u}$. In fact, many wave-generating processes in the troposphere are quasi-stationary relative to the high mean flow speeds typical of the middle atmosphere. For example, topography can excite stationary waves which propagate vertically in winter westerlies, provided that the mean flow does not change sign in the direction of wavevector orientation (Lindzen, 1981).

It is useful to separate two classes of quasi-stationary gravity waves. First, there are waves of relatively *high* intrinsic frequency. These are referred to as simple, non-inertial gravity waves, and are usually hydrostatic (requiring $|\hat{\omega}| >> N$). Second, there are distinctly inertia-gravity waves, having intrinsic frequencies near the inertial frequency f. While in reality a continuum between the two types of wave exists, the quantitative difference in wave propagation is quite substantial.

a. Simple non-inertial gravity waves

Extensive discussion of these waves appears in Dunkerton and Butchart (1984). Cases relavant to the winter middle atmosphere are considered, using satellite-derived geostrophic wind fields to assess gravity wave transmission through the stratosphere. Pertinent conclusions of this study will be reviewed here.

First, the group velocity of gravity waves includes a horizontal component. However, the vertical group velocity of quasi-stationary simple gravity waves is much larger than the horizontal component away from the

critical level ($\hat{\omega} = 0$); thus the net horizontal motion of a simple gravity wave packet will be small as these waves traverse the stratosphere. Altogether this propagation requires one to a few hours for these waves, typically. An exception occurs when a critical level is present; here, the vertical group velocity is zero and the horizontal component is equal to $\bar{u}$. However, for simple waves it appears that dissipation and/or wavebreaking will prevent such a horizontal drift from being a significant effect.

Second, the ray tracing equations describe refraction of the horizontal wavevector due to shear of the mean flow and (for long waves only) the beta-effect. However, for the reasons mentioned in the above paragraph, the horizontal refraction is likewise a small effect for quasi-stationary simple waves of O(50-200km) horizontal wavelength.

Third, as a result of these considerations it is an excellent approximation to consider exactly vertical ray paths for these waves. This is, in fact, the usual approximation (Lindzen, 1981; Matsuno, 1982; Holton, 1982; Dunkerton, 1982). A major goal of Dunkerton and Butchart (1984) was to assess the effect of stratospheric sudden warmings on gravity wave transmission. Our most significant result is that sudden warmings act to polarize the transmitted gravity wave spectrum (in the same manner as the excitation process itself, presumably). A point previously over-looked in discussions of gravity wave propagation is that the sudden warming involves not only the reversal of the zonally-averaged flow (which has been used by Lindzen, 1981, and Holton, 1983 to assess changes in transmission during warmings) but also the development of large-amplitude planetary waves. Specifically, a major warming is still characterized by local mean westerlies over much of the globe; therefore the situation for vertically-propagating gravity waves in such regions is largely unchanged from the unperturbed winter state.

Fig. 1 shows a polar stereographic plot of average transmitted wavevector assuming isotropic initial excitation for February 22, 1979, using derived geostrophic winds in this major wave 2 warming. The average wavevector on the 1 mb surface, shown in the Figure, represents the average orientation of transmitted gravity waves which have been allowed to propagate from 100 to 1 mb. At once it is apparent that the major warming has had a

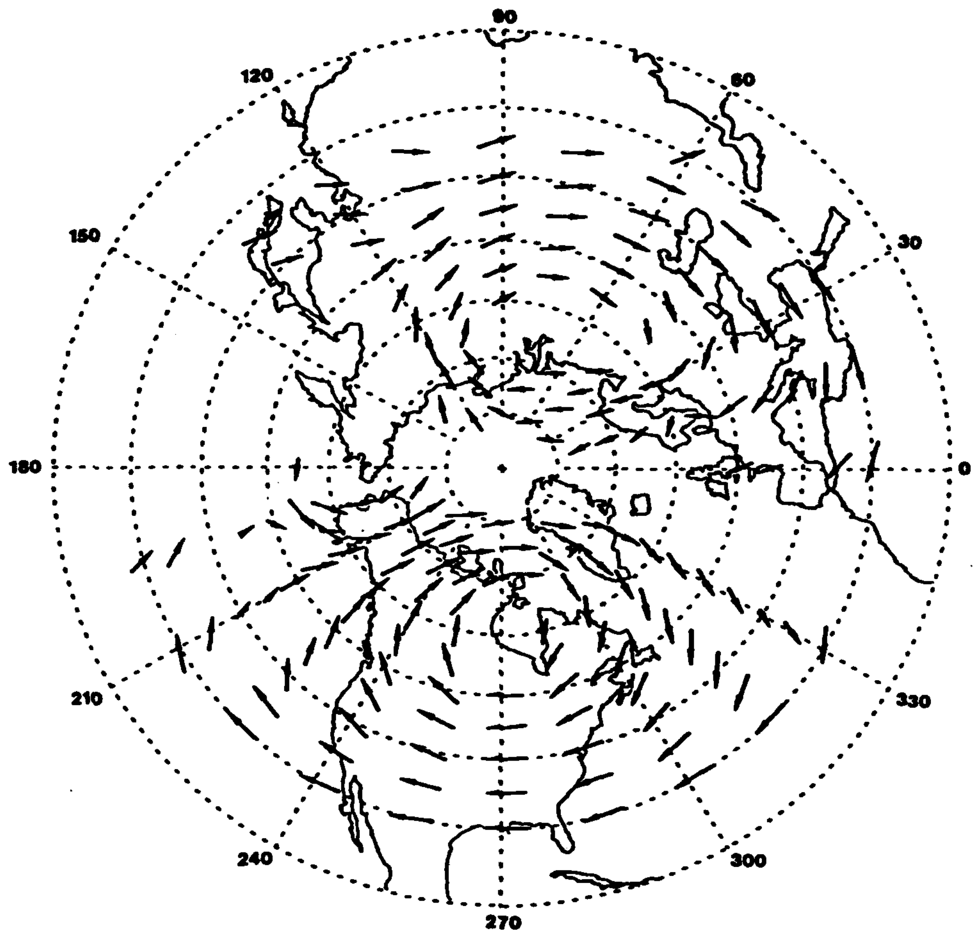

Figure 1. Average transmitted wavevector of quasi-stationary gravity waves on the 1 mb surface for February 22, 1979.

major effect in reducing transmission only in those regions where local easterlies dominate (in high latitudes north of the low centers waves of opposite orientation are transmitted also). South of the low centers the situation is much like the unperturbed state; here, local westerlies allow vertical propagaton of quasi-stationary waves. Using the zonally-averaged flow to assess transmission would have incorrectly precluded any propagation whatsoever north of 55 N. Zonally-dependent transmission will therefore have profound consequences for the mesosphere above a sudden warming (Dunkerton and Butchart, 1984).

b. Inertia-gravity waves

Waves in this class are characterized by intrinsic frequencies in the vicinity of the Coriolis parameter. Physically, the waves have a Coriolis-induced perturbation velocity component transverse to the horizontal wavevector orientation. Examination of their dispersion relation

$$\hat{\omega}^2 = \frac{N^2(k^2+\ell^2)}{m^2} + f^2 \tag{2.2}$$

indicates that inertia-gravity waves will tend to have a fine vertical structure, just as is observed. Also, the vertical group velocity is much slower than for the shorter simple waves.

As a result, horizontal ray movement and refraction are significant effects in inertia-gravity waves. Discussion to this effect has been given by Dunkerton (1984). Fig. 2 illustrates ray paths and ray times for a particular case of long waves propagating in middle atmosphere winds. The initial horizontal wavelength is 400km and the waves are intially propagating vertically at the tropopause. Thereafter, the horizontal mean wind shear refracts the wavevector, an effect most pronounced near the inertial cutoff, causing propagation into the polar night jet. These effects are even more important at longer scales (e.g. 800 km). The ray time is also a strong function of the proximity to the inertial cutoff; in Fig. 2, it will be noted that this time is now on the order of several hours to a few days (in contrast to the simple waves).

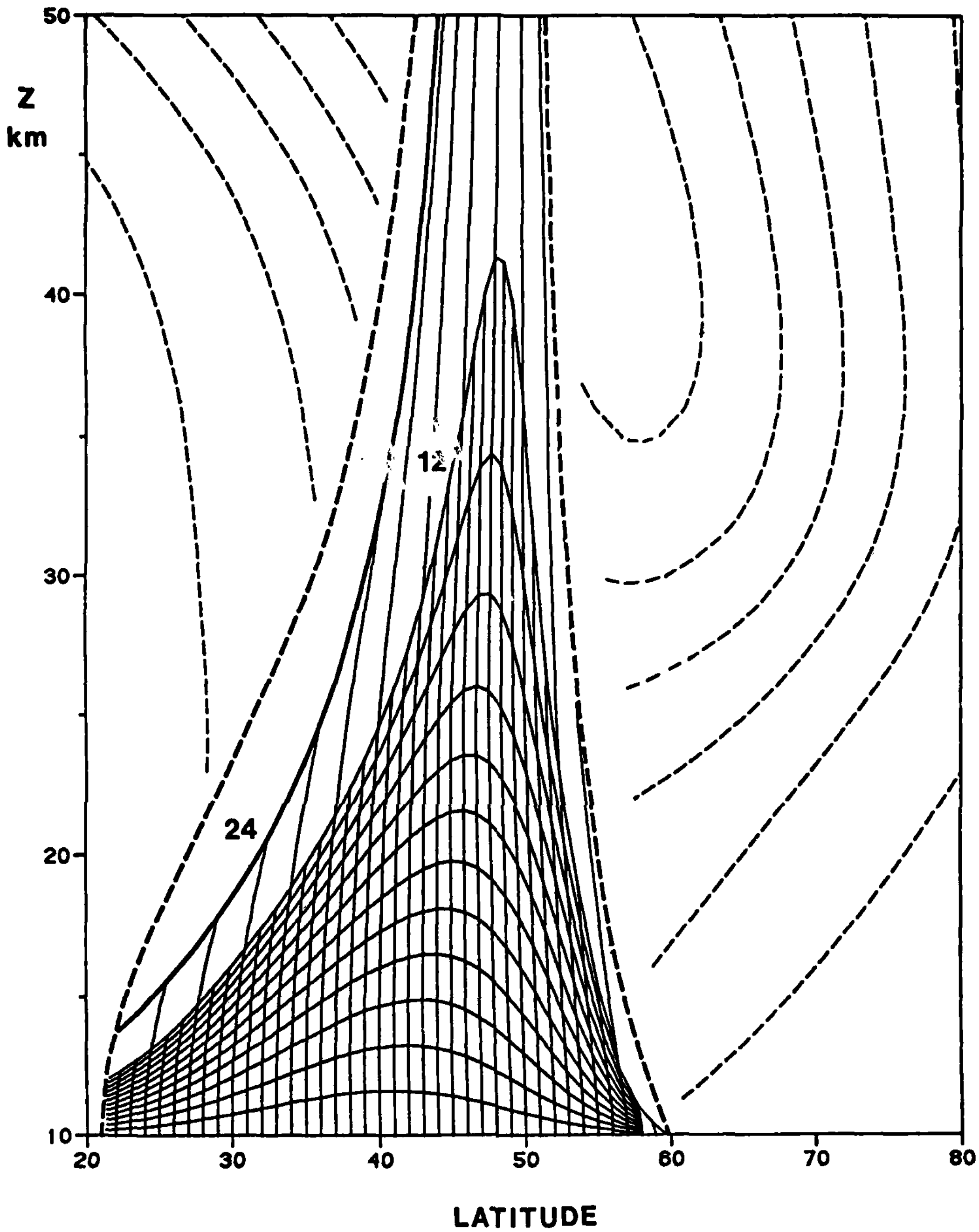

Figure 2. Ray paths and ray times for long gravity waves propagating in the winter wind profile shown (dashed lines).

Implications are 1) gravity wave packets do not necesarily arrive in the mesosphere directly above their source of excitation, particularly for inertia-gravity waves; typically several thousand kilometers can be traversed by these waves horizontally while they are in the stratoshere; 2) when critical layer interaction occurs, there is a distinct possibility of Kelvin-Helmholtz instability in the wave+mean field, in contrast to the simple waves; 3) the inertia-gravity waves entering the stratosphere will have undergone extensive horizontal refraction, leading to a final wavevector orientation much different than the one originally excited. More speculatively, inertia-gravity wave normal modes may exist in the polar night jet structure.

Observations indicate widespread breakdown of inertia-gravity waves in the lower stratosphere. Fig. 2 confirms this result in lower latitudes where weak winds are encountered. As discussed in Section IV, this breakdown may be a significant effect in constituent mixing, since the process differs from that of the simple waves.

III. PROBLEMS IN GRAVITY WAVE, MEAN-FLOW INTERACTION

Two specific problems are addressed in this section. First we use a numerical model of gravity waves to assess the effects of saturation and self-acceleration. Saturation occurs when potential temperature surfaces turn over in the (x,z) plane; the resulting convective instability prevents the wave amplitude from exceeding the saturated value. In the model, convective adjustment is used to describe this process (refer to Dunkerton and Fritts, 1984, for a discussion of the model and the convective adjustment parameterization). Self-acceleration occurs when the wave deposits its momentum in the mean flow; the wave frequency relative to the ground then changes if the mean flow acceleration occurs rapidly enough.

Second, a semi-analytic model of gravity wave interaction is compared to these model simulations.

In the particular case considered here, a wave of vertical velocity amplitude 2 ms^{-1} is excited at the lower boundary, corresponding to some level of the troposphere. Vertical propagation then ensues over a 100 km deep model domain. The wave is stationary, with intrinsic propagation to the west in a hyperbolic tangent profile of mean wind. Details of this case are given in Fritts and Dunkerton (1985a). Here, we focus on the wave-induced mean flow change to diagnose saturation and self-acceleration effects.

Fig. 3 shows the mean flow change brought about by the wave, for two cases: without convective adjustment (dashed lines) and with convective adjustment (solid lines) at three times (4.5, 5.0, and 5.5 wave periods). For the case without convective adjustment we note the following observations. First, the mean flow acceleration is negative, i.e., in the direction of intrinsic phase propagation. Second, the induced mean flow is significantly negative. Even though the wave is forced as a stationary wave with zero phase speed, therefore having an initial critical level at $\bar{u} = 0$ (at nondimensional height .6) the self-acceleration of wave frequency has "displaced" the critical level to some significantly negative value. This value, in fact, is perhaps 30 ms^{-1} or more less than zero. Third, there is significant penetration beyond the initial critical level.

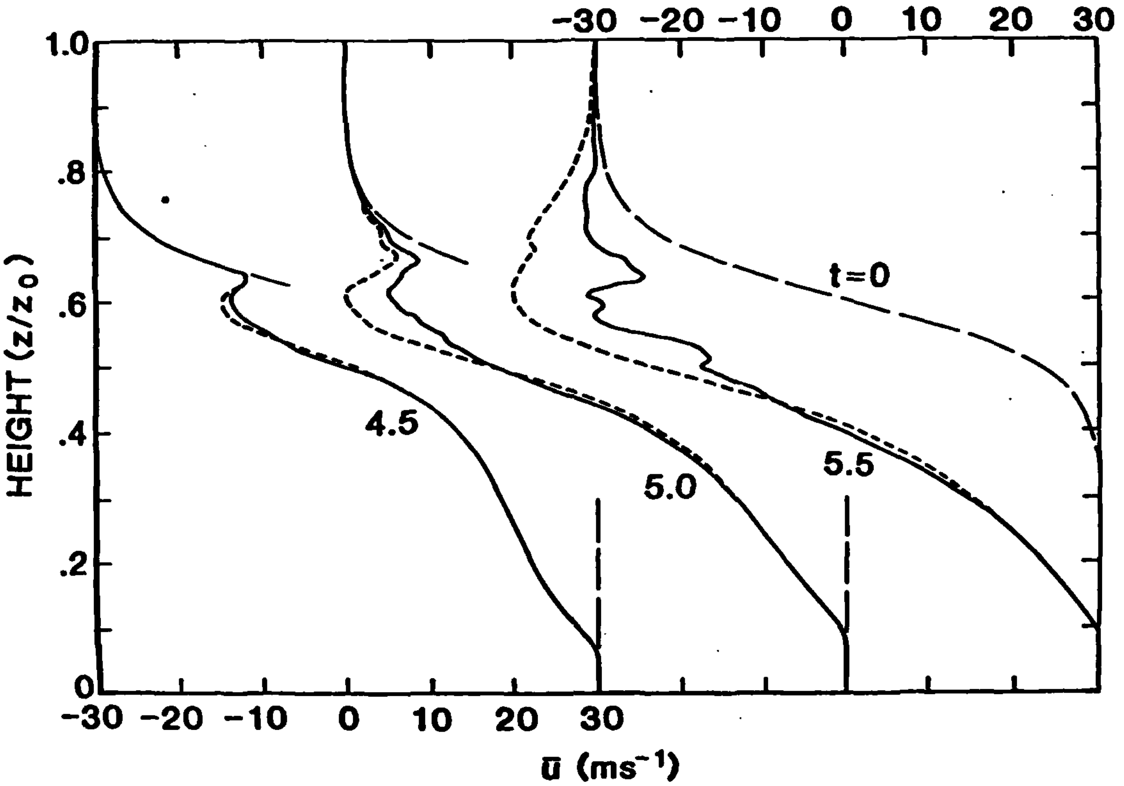

Figure 3. Wave-induced mean flow changes at three times for two model experiments, with and without convective adjustment.

In the case with convective adjustment we note the following observations. First, saturation tends to reduce the allowed momentum fluxes and hence, the wave-induced mean flow acceleration, a process that increases in importance with time. Second, however, the saturation process does not prevent self-acceleration from occurring. Once again the effective critical level is large negative. Third, there continues to be significant vertical penetration above the initial critical level.

The most important implication of these results is that observed phase speeds in the atmosphere need not correspond with those present at the level of wave excitation. Also, the presence of an initial critical level at some height does not guarantee the absorption of the gravity wave since the phase speed might change due to wave transience and/or breaking during its vertical propagation.

How do these conclusions compare with a semi-analytic model of gravity waves? (See Section 2 of Dunkerton and Fritts, 1984, for discussion of the semianalytic model.) Fig. 4 displays results with this model for the same wave parameters and amplitude. The same two cases are shown at the same three times. Overall there is good agreement with Fig. 3, but the quantitative differences are also significant. There is less penetration of the critical level in Fig. 4. Secondarily, there is somewhat less self-acceleration; but saturation remains an important constraint.

We attribute the discrepancy in vertical penetration of the initial critical level to a non-WKB effect, in the sense that the initial wave forcing induces a range of phase speeds which, in turn, see slightly different critical levels. In this respect, our model simulation in Fig. 3 conforms more closely to real-life situations where impulsive-type forcings are present. However, we continue to regard Fig. 4 as indicative of a fixed-forcing situation.

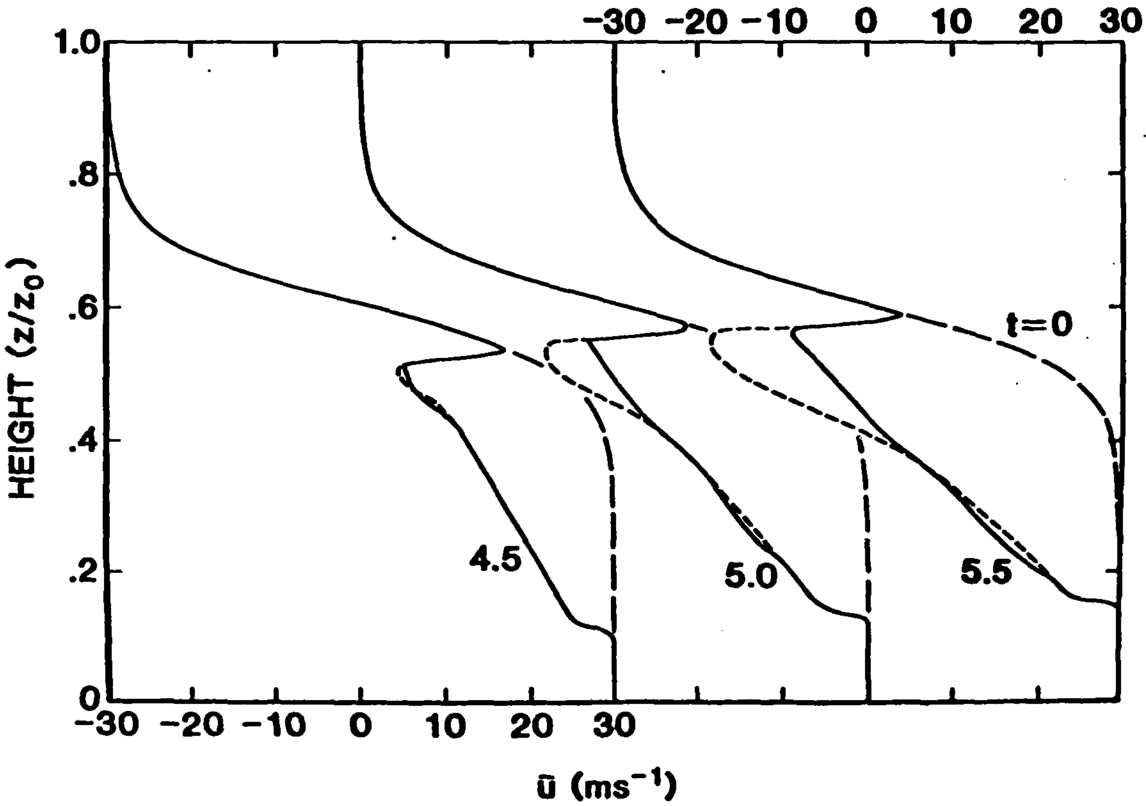

Figure 4. As in Fig. 3, but for the semianalytic model.

IV. CONSTITUENT MIXING IN GRAVITY WAVE BREAKDOWN

Here we review the analysis of Fritts and Dunkerton (1985b) dealing with constituent mixing in gravity wave breakdown. Our discussion was motivated by the saturation hypothesis of Lindzen (1981) who first suggested that convective instability in gravity wave motion acts to limit wave amplitudes to a saturated value. Lindzen assumed that the turbulent Prandtl number of the convective turbulence was effectively unity, acting on the wave amplitude independently of the local wave phase. In Fritts and Dunkerton (1985b) we suggest that this assumption is inconsistent with other models of localized turbulence in gravity wave motion, which ultimately implies a very large turbulent Prandtl number for a convectively unstable gravity wave.

It is not difficult to follow the logic of this argument. Convective instability is expected to break out in those regions where potential temperature surfaces have overturned in the (x,z) plane. Assuming that the ensuing turbulence acts to restore the potential temperature configuration to near neutral stability, it is apparent that this requires a locally downgradient flux of potential temperature. However, because the local gradient of potential temperature is reversed relative to the mean (statically stable) profile, it appears that convective instabilities in gravity wave motion act countergradiently relative to the mean.

In Fritts and Dunkerton (1985b) we evaluate the total flux of constituents due to a superadiabatic gravity wave motion in which there is some imposed vertical eddy diffusivity which has a mean and wave component. As shown in Fig. 5 here for a particular case, the eddy diffusivity is maximum in the unstable region. Also shown is the eddy diffusivity that results from the Orlanski-Ross parameterization. (The latter is actually much more localized, eddy diffusivity varying like lapse rate to the 1/3 in the unstable region <u>only</u>.) As it turns out, the particular case shown in Fig. 5 has very small total flux of potential temperature in the sense that the net mean tendency of potential temperature is just a small fraction of $\frac{\partial}{\partial z}(\overline{\nu\theta_z})$. Greater localization of convection increases the countergradient tendency, and vice versa.

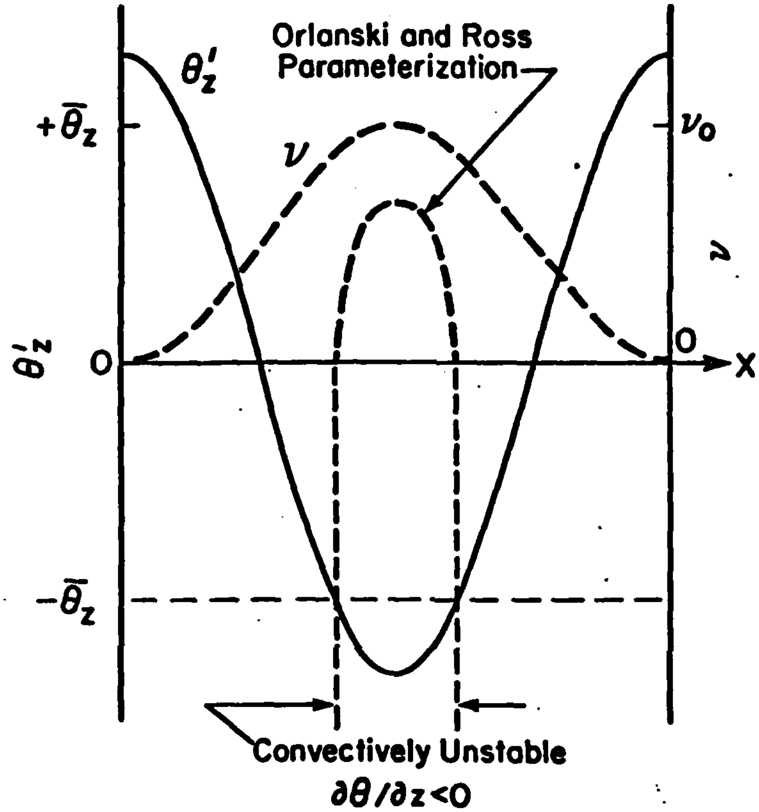

Figure 5. Perturbation potential temperature gradient for a superadiabatic gravity wave motion. Postulated eddy diffusivities shown as heavy dashed lines.

Several implications of this result were discussed by Fritts and Dunkerton (1985b). Of practical importance are the facts that a field of convectively saturating gravity waves in the mesosphere will not act to redistribute potential temperature or photochemical constituents to the extent implied by Lindzen (1981). At the same time, these waves still have a crucial impact on the angular momentum balance of the mesosphere. Theory therefore agrees qualitatively with observations on all three counts.

A second observation should also be made. For inertia-gravity waves, dynamical instability may precede convective instability. Such may be the case in simple gravity waves also if the mean shear is strong. In such cases the ensuing turbulence will not be restricted to regions of convective instability, and the eddy diffusion will not be sufficiently localized. Thus a significant downgradient flux of consitituents will be allowed when, e.g. inertia gravity waves breakdown via dynamical instability. This result will have important consequences in the lower stratosphere where such instabilities in inertia-gravity waves are observed.

V. CONCLUSION

Many theoretical problems remain to be addressed in gravity waves. Most of the relevant questions can only be addressed with numerical modelling, as in Dunkerton and Fritts (1984) and Fritts and Dunkerton (1985a). These issues include the role of nonlinearity in gravity wave critical layer development, whether convective or dynamical instabilities preclude formation of the Maslowe nonlinear critical layer, what role does wave superposition play in wave saturation, and is it possible for a field to gravity waves to saturate without going convectively unstable? Our research plans are structured in order to carry out a systematic investigation of these and other relevant issues. Modelling of inertia-gravity waves has also been proposed by the author.

It is appropriate, however, to conclude this report with an assessment of observational goals. Broadly, gravity waves need to be investigated at three levels of the middle atmosphere, and at a representative (i.e., judicious) selection of stations spaced around the globe. First, gravity waves in the mesosphere need to be examined systematically so that a gravity wave climatology can be constructed. Of particular importance are the gravity wave momentum flux (and its divergence) and the associated eddy diffusion. Seasonal variations are crucially important here, as well as any special effects due to sudden stratospheric warmings. Second, in the lower stratosphere the morphology of inertia-gravity waves must be established. Present observations are seriously limited in scope here, having been obtained at only a few locations and during rather specialized experimental campaigns. The issue of inertia-gravity wave breaking is simply too important for photochemical considerations to be overlooked in this region. Finally, there is the middle and upper stratosphere. These levels are too high for balloons, and lie in the "echo gap" of MST radars. Satellite remote sensing lacks adquate vertical resolution for gravity waves, and rocketsondes (which have observed the gravity wave spectrum at all levels) are quite costly. Lidar observations would seem appropriate, being a portable and low-cost means of observing the stratosphere (although meteorological conditions must be

favorable). The predictions of Dunkerton and Butchart (1984) suggest occasions on which gravity wave breaking in the middle and upper stratosphere may be important, such as in local regions of major warmings.

Obviously the present state of observational capability has done much to clarify the gravity wave spectrum (an excellent review by Fritts, 1984, should be consulted here). However, it is also clear that there is something tantalizing about the problem at hand; each observation, obtained with laborious effort and sometimes nontrivial cost, seems to suggest that more observations are needed! More station locations need to be implemented (particularly in the tropics and Southern hemisphere) and routine observations need to be taken over periods of several years. It is hoped that the next two decades will lead to a significant increase in our understanding of the role of gravity waves in the middle atmosphere.

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